

PIPELINE DAMAGE PREVENTION THROUGH THE USE OF LOCATABLE MAGNETIC PLASTIC PIPE WITH A UNIVERSAL LOCATOR

FINAL REPORT

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SUMMARY

The primary objective of the subject DOT-funded project is to develop magnetic plastic polyethylene (PE) gas distribution pipe materials containing less than about 12% by weight of magnetic powder and that can be accurately located from above ground using a hand-held magnetic locator.

To achieve the research objectives, it was determined that to identify the effects and range of many variables, a large body of information and data can be generated and evaluated for the least cost by manufacturing in the laboratory, under controlled conditions, compression molded (CM) PE plaques. These magnetic CM plaques can be expeditiously and cost-effectively made in the laboratory using various amounts, concentrations, and types of magnetic powder materials and magnetization techniques. GTI made several CM PE plaque materials containing different types and amounts of magnetic powder materials in the form of single and multiple layers to simulate extruded single-layer or multi-layer magnetic PE pipes. These new plaque materials were magnetized by GTI using several different magnetization techniques including axial pulse magnetization, transverse magnetization, and spiral magnetization.

The work activities in each of the four phases in the subject DOT project included performing many tasks and addressing several questions. GTI completed all the milestones and performed all the work tasks in the DOT project involving the following activities:

1. Made under controlled laboratory conditions many new single- and multi-layer compression molded (CM) PE plaques containing different types of magnetic powder materials.
2. Two new magnetic powder filler materials were identified and used extensively in the subject DOT-funded project for making single-layer and multiple-layer CM PE plaque materials because of their high magnetic properties:
 - a. One of the new magnetic powder materials used for making CM PE plaques is a Barium-base (Ba) material, designated as HM 185.
 - b. The second magnetic powder that was used in making new CM PE plaques is a Niobium-base (Nb) material, designated as MQP 16-7.
3. Made several single- and multiple-layer CM PE plaques with different amounts or weight percentages (%w) of magnetic powder HM 185 including 24%w, 18%w, 12%w, etc.
4. Made several single- and multiple-layer CM PE plaques with different amounts or weight percentages of magnetic powder MQP 16-7 including 24%w, 18%w, 12%w, etc.
5. Magnetized the new CM PE, made with HM 185 and MQP 16-7, using both transverse and axial magnetization techniques.
6. Experimentally determined and measured the magnetic field strength of the axially and transversely magnetized new CM PE plaques containing

various amounts of the HM 185 and the MQP 16-7 magnetic powder materials.

7. Conducted numerous laboratory tests to compare the magnetic field strength of the newly made plaque materials containing the MQP and the HM 185 powder with the previous proof-of-feasibility (POF) pipes that contained 24%w of the HM 130 powder.
8. Many laboratory tests were performed to determine experimentally the magnetic field and whether or not saturation levels were achieved with the POF HM 130 transverse spirally magnetized PE pipes.
9. Conducted several experiments and determined that full magnetic saturation was induced in the POF HM 130 transverse spirally magnetized PE pipe.
10. Verified experimentally the accuracy and reproducibility of the magnetization techniques, test data, and test results on the basis of magnetization work performed independently by another company on new magnetic plaque materials made by GTI.

OBJECTIVE OF THE DOT R&D PROJECT

The primary goal of the subject DOT-funded research project is to develop magnetic plastic polyethylene (PE) gas distribution pipe materials that can be accurately and reliably detected from above ground using a hand-held magnetic locator. The specific objective of this project involves the development of locatable PE pipe materials having sufficiently high magnetic field but with reduced amounts of magnetic powder compared to the proof-of-feasibility (POF) magnetic PE pipe materials that were previously developed by GTI prior to the subject DOT funding.

The subject DOT project was funded by the US DOT and GTI. GTI provided significantly more than 50% co-funding in the subject project.

IMPORTANT RESULTS AND CONCLUSIONS

Many important results, findings and conclusions were established and validated in the subject DOT project. The most important conclusion is that new plastic PE pipe materials containing less than about 6%w of the newly identified magnetic powder MQP have a sufficiently high magnetic field that would allow them to be readily located from a distance of three-to-five feet from above ground.

Several additional important results and findings are summarized as follows:

- The laboratory tests showed that plaques made with about 6%w of the Nb-base MQP 16-7 magnetic powder have substantially greater field strength than that measured for the POF pipes made with 24%w of HM 130 magnetic powder.
- Numerous laboratory tests showed that for the same weight percent or amount of magnetic powder, the field strength of new plaque materials made with the Nb-base MQP 16-7 magnetic powder is greater than that of the CM plaques made with HM 185 magnetic powder.
- The laboratory test data showed that the magnetic field of the new plaque materials made with 12%w of the Ba-base HM 185 powder is greater than the field measured for the previous POF pipe materials containing as much as 24%w of the HM 130 powder.
- The amount of magnetic powder can be reduced to less than about 6% by weight (%w) using Nb-base MQP 16-7 magnetic powder. With 12%w of the MQP 16-7 powder, the field strength is several times greater than the POF magnetic PE pipes containing 24%w of HM 130 magnetic powder.
- Many laboratory tests performed on the new magnetic PE plaque materials showed that axial magnetization can induce a greater magnetic field and can provide many additional advantages compared to transverse magnetization or spiral magnetization.
- Axial magnetization is superior to transverse or spiral magnetization for optimizing the magnetic field strength and the consequent detection of the underground magnetized plastic pipe.
- The laboratory tests showed that pulse axial magnetization (PAM) has the advantage of inducing a magnetic field with a resultant strength that can be easily increased or decreased during pipe manufacturing.
- Also, the test results showed that PAM has the advantage of inducing dipoles along the axial direction with a period that can be easily altered and used to identify the type of pipe field application.
- Several laboratory tests showed that with axial magnetization, the field strength in the pipe specimen or the CM plaque is optimum with induced aligned dipoles, i.e. N-S-N-S-N-S ...compared to that induced with opposite dipoles, i.e. N-S-S-N-N-S-S-N-....
- Most importantly, the test results demonstrated that for test specimens with the same type and percent weight of magnetic powder, PAM induces a field greater than that induced with either transverse magnetization (TM) or spiral magnetization (SM).

- The magnetic field strength is the same for the same concentration of the magnetic powder per unit volume of pipe/plaque material. The greater the magnetic powder concentration per unit volume of the total material the greater is the field. Hence, concentrating the magnetic powder in a surface strip or in a co-extruded layer would provide a stronger localized magnetic field than uniformly distributing the magnetic powder over the entire pipe volume.
- The laboratory tests showed that the magnetic field strength increases with increasing length of plaque or pipe test specimen and attains a maximum asymptotic constant value for a specimen length of about 30 to 48 inches.
- Also, many experiments showed that for pipes magnetized axially, the greatest detectable field is obtained by traversing the pipe axially; the detectable field decreases with the orientation of the pipe locator relative to the pipe. That is, for pipes magnetized axially using the axial pulse magnetizer, the greatest magnetic detectable field is obtained by orienting the pipe collinearly with or by traversing the pipe axially relative to the locating magnetometer instrument.
- The laboratory test results showed that TM induces dipoles across the pipe diameter with a resultant field equal to that induced with spiral TSM.

BACKGROUND

Prior to DOT funding of the subject project, GTI completed the POF phase that involved the development of magnetic plastic PE gas pipe materials. To make the POF magnetic pipe, the PE resin was mixed and compounded with a strontium-barium-ferrite (Sr/Ba) magnetic powder. The Sr/Ba magnetic powder is designated as HM 130; it was purchased from Hoosier Magnetics, Inc. The compound consisting of the PE resin and the Sr/Ba magnetic powder was then made into palletized form that was used to extrude magnetic medium-density (MD) PE and high-density (HD) PE gas pipes. After the magnetic PE pipe containing the HM130 magnetic filler was extruded and cooled during the manufacturing process, the pipe passed through the cylindrical bore i.e. the annular cavity of a specially designed rotating “Permanent Magnet” (PM) magnetizer.

Figures 1 and 2 are photographic views depicting the PM having a rotating chassis. The PM magnetizer consisted of several permanent magnets, arranged in the form of a modified Halbach Dipole, mounted around the circumference of a chassis that rotated around the cylindrical bore through which the pipe passed. Figure 3 is a schematic illustration of the Halbach Dipole field of the specially designed rotating “Permanent Magnet” used to magnetize a 2- and 4-inch pipe in the POF phase. The field strength of this “Permanent Magnetizer” is in the range of 6500G to 6000G. It should be noted that: 10^4 Gauss (G) = 1 Tesla (T).

The rotating PM magnetizer caused the pipe to be uniformly magnetized transversely across the diameter. Because of its rotational motion around the pipe, the magnetizer caused the magnetic particles in the pipe to be magnetized in the form of a periodic spiral having an axis coincident with the pipe axis. This POF transverse spiral field is depicted graphically in Figure 4.

In the POF phase several field experiments were performed on the developed magnetic PE pipes with the transverse spiral field to determine whether or not they can be located from above ground using commercially available magnetometer locators. In these experiments the magnetic PE pipes were installed underground at depths ranging from about three to about five feet. In these field tests it was experimentally determined that to accurately locate the magnetic pipes from above ground: 4-inch and larger diameter pipes require an amount of about 17% by weight (w) of the HM 130 powder; and 2-inch and smaller diameter pipe sizes require an amount of about 24%w of the HM 130 powder. In the POF, a specially designed and manufactured hand-held three-axis magnetic locator was also used to locate the magnetic PE plastic pipe from above ground.

The specially compounded and extruded HM 130 POF magnetic PE pipe materials were made by a major US pipe manufacturer. The cost of the POF magnetic PE pipe was determined to be about twice the cost of typical commercialized PE pipes. This high cost resulted primarily from the need to make the compounded PE resin and magnetic powder into pellets/beads prior to extrusion. The process involving making the compound into pellets is required because of the relatively high concentrations of 17%w and 24%w magnetic filler powder. By reducing the magnetic filler concentration to about 16%-14%, the cost of extruding the magnetic PE pipe could be reduced by about 50%. The POF pipe manufacturers indicated that with concentrations not exceeding about 16%-14%w of

magnetic powder, the plastic PE resin containing the magnetic powder could be directly extruded into pipe form thus eliminating the additional cost incurred for producing pellets.



Figure 1. Close-up Photographic View of the Rotating Permanent Magnet Showing a Transversely Magnetized Extruded PE Pipe



Figure 2. Photograph of the Rotating Permanent Magnet Magnetizer

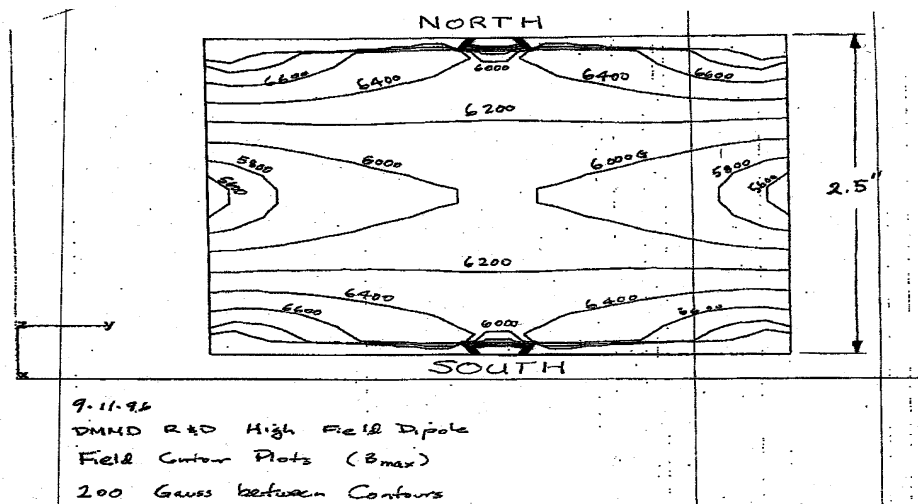


Figure 3. Schematic illustration of the Halbach Dipole Field Created By the “Permanent Magnet” Magnetizer

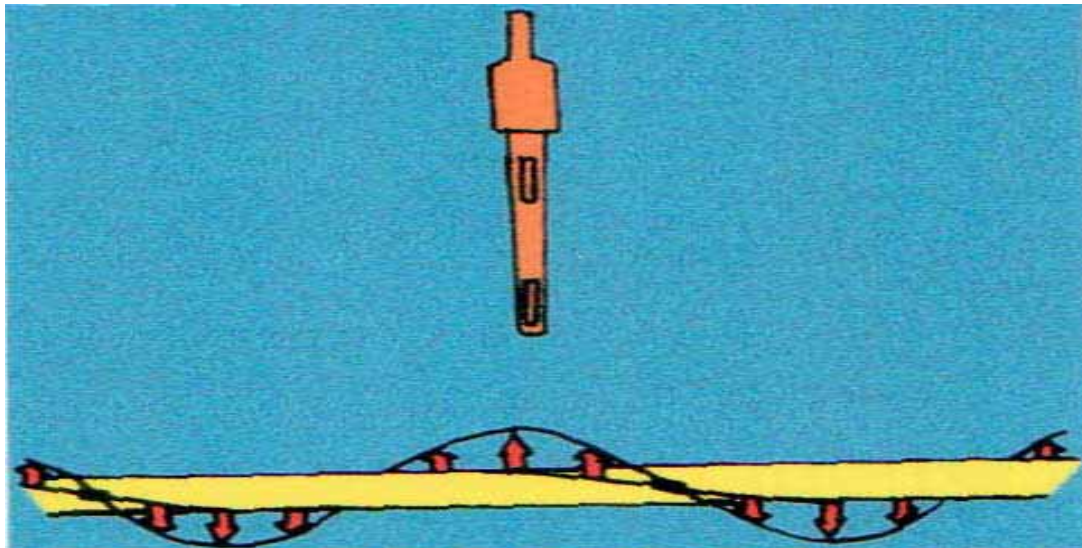


Figure 4. Schematic Illustration of the POF Spiral Transverse Magnetic Field Induced in the Pipe Using the Rotating Permanent Magnet

SCOPE OF THE R&D WORK COMPLETED IN THE DOT PROJECT

The R&D work tasks in the subject DOT-funded project included performing four phases and completing four major milestones. Each phase and milestone consisted of several tasks and work activities. All of the four major phases and milestones making-up the work scope in the subject DOT project were addressed and completed. The subject DOT project was funded by the US DOT and GTI. GTI provided more than 50% co-funding in the subject project.

Prior to DOT-funding of the subject project, GTI developed the POF magnetized pipes consisting of polyethylene resins compounded with a Strontium/Barium magnetic powder designated as HM 130. In the POF PE pipes, a transverse spiral magnetic field was induced using a specially designed rotating permanent magnet shown in Figures 1 and 2. In several field tests, it was experimentally determined that to accurately locate the POF magnetic pipes from a distance of about 3 to 5 feet from above ground: an amount of about 17% by weight (%w) of the HM 130 powder was required for 4-inch and larger diameter pipes; and an amount of about 24%w of the HM 130 powder was required for 2-inch and smaller diameter pipes. Several field and laboratory experiments showed that the magnetic field strength of the HM 130 POF magnetic pipes, with the transverse spiral magnetic field, was sufficiently high for the pipes to be located from above ground.

The cost of the POF HM 130 magnetic PE pipe was about twice the cost of commercial PE pipes. This high cost resulted primarily from the need to make the compounded PE resin and magnetic powder into palletized form prior to extrusion. The palletized form was required because of the high concentrations of 17%w and 24%w of the HM 130 magnetic powder in the PE pipe resin. It was determined that by reducing the magnetic powder concentration to about 14% or less, the palletized form would not be required for making the pipe and hence the cost of extruding the magnetic PE pipe could be reduced by about 50%.

The primary objective of the subject DOT-funded project was to reduce the amount of magnetic powder used in PE pipes to less than about 14% (by weight) in order to reduce the manufacturing cost of the magnetic PE pipe. Another objective was to maintain a magnetic field strength equivalent to or greater than the POF magnetic PE pipe with HM 130 powder.

In the development and testing work activities undertaken by GTI in the subject DOT project the field strength of the POF PE pipes containing 24% HM 130 magnetic powder was then used as a benchmark reference because previous field tests showed that the POF pipe is locatable from above ground.

To achieve the research objectives, it was determined that to identify the effects and range of many variables, a large body of information and data can be generated and evaluated for the least cost by manufacturing in the laboratory, under controlled conditions, compression molded (CM) PE plaques. These magnetic CM plaques can be expeditiously and cost-effectively made in the laboratory using various amounts, concentrations, and types of magnetic powder materials. The magnetic CM PE plaques can be made into single or multiple layers to simulate extruded single-layer or multi-layer magnetic PE pipes.

The work activities in each of the four phases in the subject DOT project included performing many tasks and addressing several questions. GTI performed all the major tasks in the DOT project involving the following activities:

- Many laboratory tests were performed to determine experimentally the magnetic field and whether or not saturation levels were achieved with the POF HM 130 transverse spirally magnetized PE pipes.
- Conducted several experiments and determined that full magnetic saturation was induced in the POF HM 130 transverse spirally magnetized PE pipe.
- Made under controlled laboratory conditions many new single- and multi-layer compression molded (CM) PE plaques containing different types of magnetic powder materials.
- Two new magnetic powder filler materials were identified and used extensively in the subject DOT-funded project for making single-layer and multiple-layer CM PE plaque materials because of their high magnetic properties:
 - One of the new magnetic powder materials used for making CM PE plaques is a Barium-base (Ba) material, designated as HM 185.
 - The second magnetic powder that was used in making new CM PE plaques is a Niobium-base (Nb) material, designated as MQP 16-7.
- Made several single- and multiple-layer CM PE plaques with different amounts or weight percentages (%w) of magnetic powder HM 185 including 24%w, 18%w, 12%w, etc.
- Made several single- and multiple-layer CM PE plaques with different amounts or weight percentages of magnetic powder MQP 16-7 including 24%w, 18%w, 12%w, etc.
- Magnetized the new CM PE, made with HM 185 and MQP 16-7, using both transverse and axial magnetization techniques.
- Experimentally determined and measured the magnetic field strength of the axially and transversely magnetized new CM PE plaques containing various amounts of the HM 185 and the MQP 16-7 magnetic powder materials.
- Verified experimentally the accuracy and reproducibility of the magnetization techniques and test results on the basis of magnetization work performed independently by another company.

The research work in the subject DOT project also addressed several questions including:

- Are there significant quantitative differences between near-field measurements and far-field measurements of the pipe's magnetic field? That is
 - Does the length of a laboratory pipe sample have an effect on the measured magnetic field components and resultant?
 - What is the length of a laboratory pipe sample whose laboratory-measured magnetic field is comparable to a pipe installed in the field; that is an infinitely long pipe.

In the subject DOT-funded project, GTI manufactured under laboratory conditions a very large number of magnetic polyethylene compression molded plaques with different amounts of the two magnetic powder materials: MQP 16-7 and HM 185. Some of these CM plaques were homogeneously mixed single layers. Some plaques were two layered and others were three-layered plaques. These CM plaques simulated single, double, and triple-layered

PE pipe materials. These compression molded plaques were made using either the Ba HM 185 powder or the Nb-base MQP 16-7 magnetic powder. Both of these powders have high magnetic properties. The laboratory work showed that it is technically feasible to manufacture 2-layer and 3-layer CM PE plaques simulating a 2- and 3-layer co-extruded magnetic pipes and containing different types and amounts of magnetic powder having concentrations as high as 24%w.

The following sections describe in some detail the completed R&D work activities including the preparation of new magnetic PE materials, test procedures and laboratory experiments, magnetic field measurements, laboratory-to-laboratory test reproducibility, comparative evaluations of the magnetic field induced in the new PE materials versus that induced in the POF pipe, and results and conclusions.

PREPARATION OF MAGNETIC COMPRESSION MOLDED (CM) PE PLAQUE MATERIALS SIMULATING PIPE MATERIALS

Substantial work efforts were undertaken and numerous laboratory experiments were performed to make, under controlled laboratory conditions, several one-layer, two-layer and three-layer magnetic PE CM plaques that simulated extruded single- and multi-layer magnetic PE pipes. To achieve the project objectives expeditiously, these magnetic PE CM plaques were used to experimentally investigate the effects of various variables including the use of reduced amounts and different types of magnetic powder. Also, many laboratory experiments were conducted to evaluate the effects of implementing several different magnetization techniques to identify the one that would induce the most optimum magnetic field in the magnetic PE CM plaques. All of these laboratory experiments and trials were directed at both: reducing the amount of magnetic powder in the CM plaques simulating PE pipes and maintaining the field strength at a magnitude equivalent to or greater than that of the POF spirally magnetized PE pipes. Some of the laboratory work trials were successful and others were not; however, all of the laboratory work provided useful data and significant information on how to achieve the objectives of this project.

The magnetic PE CM plaques were manufactured in the laboratory in accordance with ASTM specification D 1928-96 for "Preparation of Compression-Molded Polyethylene Test Sheets and Test Specimens". To assure that the prototype CM plaques represent current PE gas-grade pipe materials having all the typical additives and stabilizers, several stick-pieces of a commercially marketed high-density (HD) PE 3408 gas-grade pipe material were purchased. These pipe-sticks were cut into small pieces; then, the small pipe pieces were chopped and grounded into minute flakes using a fine grinding machine. The grounded HD PE fine flakes were mixed with the magnetic powder material. For making CM plaques containing different amounts (%w) of magnetic powder relative to the amount of PE, different amounts of the magnetic powder material was mixed with the grounded PE. For instance, for making a single-layer CM plaque with 12%w of powder, an amount of 650 grams of grounded PE was mixed with an amount of 89 grams of magnetic powder. A total amount of about 739 grams of the mixture consisting of the grounded PE and the 12%w of magnetic powder was placed in a rectangular picture-frame mold.

Rectangular picture-frame molds of different sizes were used for making the CM plaques. The mold containing the mixture of grounded PE and the magnetic powder was then placed in an automated press with platens that can be heated to the required temperature of

about 180C. The press, shown photographically in Figure 5, has the required clamping force; the press can be programmed to operate at different heating-cooling-pressure cycles and time schedules necessary for making the CM plaques.



Figure 5. Photographic view of the automated programmable press used for making the magnetic CM PE plaques

**PE CM PLAQUE MATERIALS MADE USING NEWLY IDENTIFIED
MAGNETIC POWDER MATERIALS HAVING STRONGER MAGNETICS
THAN PREVIOUS POF POWDER**

Two new magnetic powder filler materials having stronger magnetic properties than the previous POF powder were identified and used for making PE CM plaques in the current reporting period of the subject DOT-funded project.

1. One of the new magnetic powder materials that was used in making new CM PE plaques is a Niobium-base (Nb) material, designated as MQP 16-7.
2. The second magnetic powder materials used for making additional CM PE plaques is a Barium-base (Ba) material, designated as HM 185.

Several CM PE plaques were made with different amounts or weight percentages (%w) of the magnetic powder HM 185 including 24%w, 18%w, 12%w, etc. Also, many CM PE plaques were made with different amounts or weight percentages of the magnetic powder MQP 16-7 including 24%w, 18%w, 12%w, etc. Some of the CM plaques were single layers consisting of the homogenous mixture of the grounded PE and the magnetic powder. Other CM plaques consisted of two-layers or three-layers. With the multi-layer plaques, at least one of the layers consisted of only the grounded PE and the other layer consisted of the homogenous mixture of the grounded PE and the magnetic powder using the weight percentage required for development work and testing. Each CM plaque test specimen was approximately 2-inch wide and about ½-inch thick. CM plaque test specimens with different lengths- - including 8.75-, 17.5-, 26.25-, and 35-inch- - were used for testing and evaluating the field induced using different magnetization techniques and magnetic powder materials.

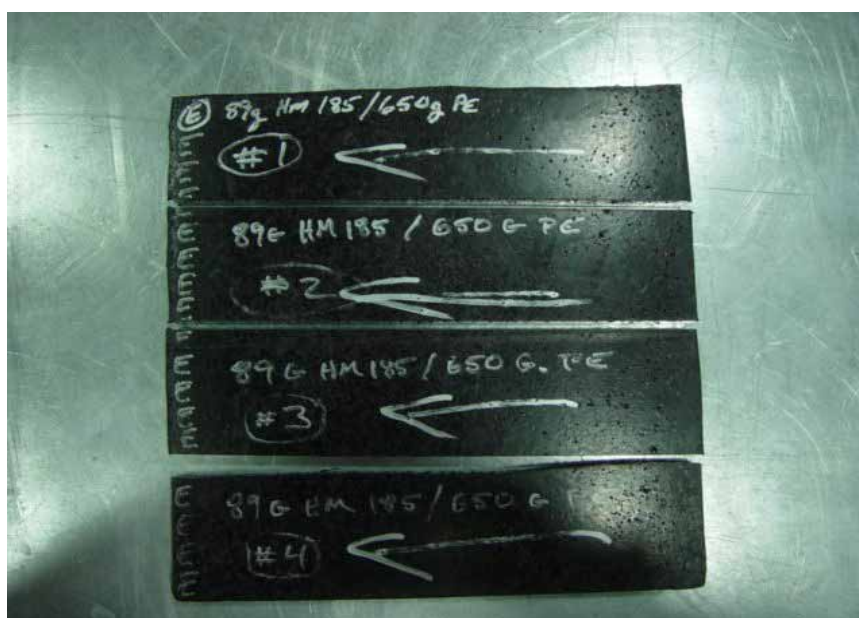
Several one-layer CM plaques were made consisting of a homogeneous mixture made-up of 650 gm of the grounded HDPE pipe and 89 gm of either the MQP 16-7 magnetic powder or the HM 185 magnetic powder. These CM plaques represent materials containing about 12%w of the magnetic filler. Figure 6 shows a few of the CM plaques with 12%w of MQP 16-7 and HM 185 magnetic powders, respectively.

Figure 6 (a) depicts a photograph of several one-layer CM plaques consisting of a homogeneous mixture made-up of about 650 gm of the grounded HDPE pipe and 143 gm of MQP 16-7 magnetic powder. Figure 6 (b) shows CM plaques consisting of about represent materials with about 18%w of magnetic powder. Figure 7 (a) shows a few CM plaques consisting of about 205 gm of grounded PE pipe material and about 205 gm of the MQP 16-7 magnetic powder. Figure 7 (b) is a photograph of a few one-layer CM plaques made with about 547 gm of the grounded HDPE pipe and about 173 gm of HM 185 or MQP 16-7 magnetic powder. These plaques represent about 24%w of the magnetic powder. The CM plaques shown in Figures 6 to 8 were all made by blending and homogeneously mixing the PE and the powder to make single layer CM plaques.

In addition to the above-described plaques, several additional CM PE plaques consisting of one-, two- and three-layers were also manufactured under controlled laboratory conditions using different amounts of either magnetic powder MQP 16-7 or magnetic powder HM 185 powder. With the three-layer plaques, each of the two outer layers consisted of about 150 gm of the grounded HDPE pipe; the magnetic powder was introduced into only the middle layer. Figure 9 (a) shows 3-layer CM plaques with the middle layer consisting of a homogeneous mixture made-up of 210 gm of the magnetic powder MQP 16-7 and 300 gm of the grounded HDPE pipe material. Figure 9 (b)) shows 3-layer CM plaques with the middle layer consisting of a homogeneous mixture of 173 gm of the magnetic powder HM 185 and 247 gm of the grounded HDPE pipe. The three-layer CM plaques shown in Figure 9 contain about 26%w of MQP 16-7 and about 24%w of HM 185, respectively. In these three-layer plaques the concentration of the magnetic powder was higher than the one-layer plaques because the magnetic filler was placed in only the middle layer.



(a) CM PE plaques consisting of 12 %w of the MQP 16-7 magnetic powder



(b) CM PE plaques consisting of 12 %w of the HM 185 magnetic powder

Figure 6. Photograph of few single-layer CM plaques made-up of about 633 gm of HDPE and 87 gm of magnetic powder (a)HM 185 and (b) MQP 16-7.

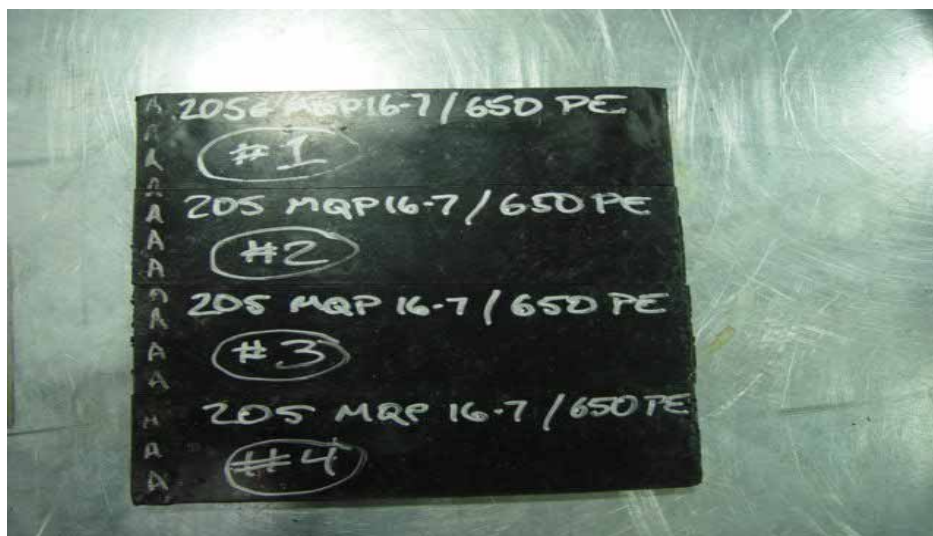


(a) CM PE plaques consisting of 18 %w of the MQP 16-7 magnetic powder



(b) CM PE plaques consisting of 18 %w of the MQP 16-7 magnetic powder

Figure 7. Photograph of few single-layer CM plaques containing 18%w of magnetic powder (a) MQP 16-7 and (b) HM185



(a) CM PE plaques consisting of 24 %w of the MQP 16-7 magnetic powder



(b) CM PE plaques consisting of 24 %w of the MQP 16-7 magnetic powder

Figure 8. Photograph of few single-layer CM plaques containing 24 %w of the magnetic powder (a) MQP 16-7 and (b) HM185



(a) Three-layer plaques with MQP 16-7 magnetic powder



(b) Three-layer plaques with HM 185 magnetic powder

Figure 9. Three-layer CM plaques consisting of (a) 26%w MQP 16-7 and (b) 24%w HM185

MAGNETIZATION EXPERIMENTS

In the DOT-funded project, numerous laboratory tests were undertaken to identify the magnetization technique(s) that would induce the greatest magnetic field in the test pipes or the above-described newly made magnetic CM PE plaque materials.

Three magnetization techniques were utilized and examined in-depth. These magnetization techniques included:

- The initial POF transverse spiral magnetization (TSM) method using the rotating Permanent Magnet magnetizer shown in Figures 1 and 2;

- Transverse magnetization (TM) using the Permanent Magnet magnetizer shown in Figure 1 but with a non-rotating stationary chassis; and
- Pulse Axial Magnetization (PAM) using a specially procured Pulse Axial Magnetizer.

Figure 10 is a photograph of the Pulse Axial Magnetizer. Figure 11 is another photograph showing both the Pulse Axial Magnetizer and the 2-inch Rotating Permanent Magnet Magnetizer in the background.

In the previous reporting periods in this project, several induction coils were designed, fabricated and used in performing pulse axial magnetization experiments. In these earlier laboratory experiments on pulse axial magnetization two shorter induction coils (3-inch and 1-inch) were extensively used; these two induction coils are shown in Figure 12. These previously made shorter induction coils did not induce an optimum magnetic field in the newly made magnetic PE materials. This is due to the fact that the full electro-magnetic capability of the Pulse Axial Magnetizer was not fully utilized with the shorter induction coils.

To utilize the optimum capability of the pulse axial magnetizer, a new 11-inch long induction coil was designed, constructed and used in the PAM experiments performed during the current reporting period. This new induction coil is shown installed on the pulse axial magnetizer depicted in Figure 10. A close-up view of the 11-inch long induction coil is presented in Figure 13. Figure 14 shows a pipe specimen inserted within the 11-inch long induction coil in preparation for pulse axial magnetization. In the current reporting period, the new 11-inch induction coil was and used in the axial magnetization experiments

Many laboratory experiments were performed to determine the effect on the induced spiral transverse magnetic field of passing a CM plaque specimen or a pipe specimen several times through the TM magnetizer. The laboratory tests showed that typically one pass of the specimen through the annular space of the Permanent Magnet was sufficient to induce an optimum transverse field.

Similarly, experiments were conducted using the PAM and the recently designed and constructed 11-inch long induction coil to determine the effect on the induced magnetic field of the number of pulses, number of dipoles, overlapping dipoles, and dipole alignment in the pipe sample or in the CM test plaque specimen. It was found that one pulse using the Pulse Axial Magnetizer was sufficient to induce an optimum axial field in the CM plaque or pipe specimen. To induce a field with axially aligned dipoles in a pipe or a plaque specimen, the specimen was inserted in the induction coil, pulsed, and then pushed through the coil in the same direction and pulsed again. Figure 15 is a schematic illustration of an axial field with aligned dipoles induced using the PAM magnetizer. To induce opposite dipoles, the specimen is pulsed, removed from the coil, re-inserted in the reverse direction through the coil, and pulsed again. Many laboratory tests showed that with PAM, an optimum field is induced with aligned dipoles N-S-N-S-N-...., as shown schematically in Figure 15.



Figure 10. Photographic View of the Pulse Axial Magnetizer and the 11-inch Long Induction Coil (Front Black Coil)



Figure 11. Photographic view of the Pulse Axial Magnetizer (front white) and the Rotating Permanent Magnet magnetizer (rear tan)



Figure 12. Magnetic Induction Coils Used in PAM experiments: top coil 3.25-inch wide and bottom coil 1.25-inch wide.



Figure 13. Close-up Photographic View of a Recently Constructed 11-inch Long Induction Coil Used for Axial Magnetization



Figure 14. Photograph Showing a Pipe Sample, Inserted Within the 11-inch Long Induction Coil, Prepared for Pulse Axial Magnetization

transversely to the probe; this is referred to as the transverse-A position or orientation. In the transverse-A position, the specimen's end face is in-line with the probe and the specimen's longitudinal axis is perpendicular to the probe.

Figures 18 (a) and (b) show test specimens placed transversely to the probe but with their centerline coincident with the probe as shown photographically in this position is referred to as the transverse-B orientation. Figure 19 presents schematics depicting the axial, 45-degree, and transverse-A and transverse-B orientations of the test specimen relative to the magnetometer probe.



(a) CM plaque specimen oriented axially (b) Pipe specimen oriented axially

Figure 16. Photographic View Depicting (a) CM Plaque Specimen and (b) Pipe Specimen Oriented Axially Relative to the Magnetometer Probe



(a) CM plaque along 45-degree direction (b) CM plaque along transverse-A direction

Figure 17. Photographs Showing a CM Test Specimen Oriented at (a) 45-degree and (b) Transverse-A Direction Relative to the Magnetometer Probe



(a) CM plaque in transverse-B orientation (b) Pipe specimen in transverse-B orientation

Figure 18. Photographic Views Depicting (a) CM Plaque Specimen (b) Pipe Specimen Oriented along Transverse B Position Relative to the Magnetometer Probe

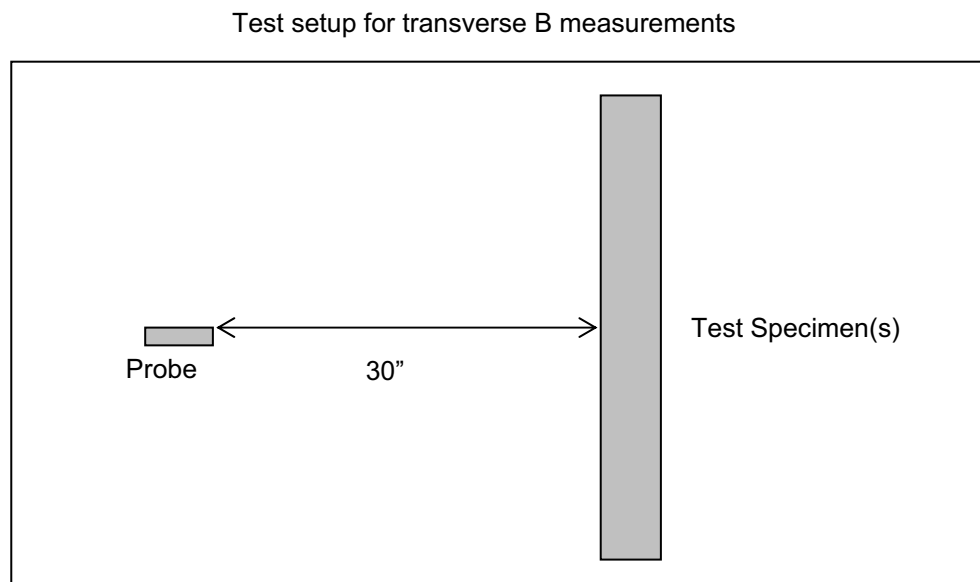
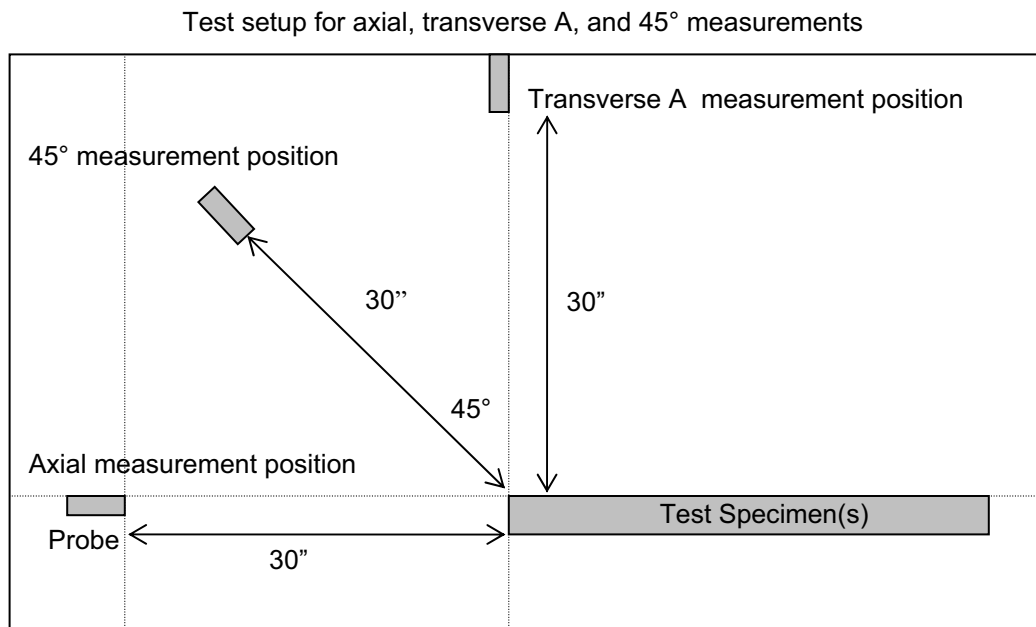


Figure 19. Schematic Illustrations of the Axial, 45-degree, and Transverse-A and Transverse-B Orientations of the Test Specimen Relative to the Magnetometer Probe

For each test specimen including the newly made CM magnetic PE test materials, the magnetic field was measured along the axial direction by placing the test sample axially relative to the magnetometer probe as shown in Figure 16. While in this axial orientation, the x-, y- and z-components of the magnetic field of the specimen were measured. The corresponding resultant or magnitude of the magnetic field of the test specimens in the axial orientation was calculated. Similarly, with the test specimen placed along the 45-degree orientation relative to the probe as shown in Figure 17 (a), the x-, y-, and z-components of the magnetic field were recorded and the corresponding resultant along the 45-degree orientation was calculated.

Also, the magnetic field along the specimen's transverse-A direction was measured by placing the specimen's end-face in-line with and transversely to the magnetometer probe as shown in Figure 17 (b). While placed in the transverse-A orientation relative to the magnetometer probe, the x-, y-, and z-components of the magnetic field of the test specimen were measured and the corresponding magnetic field resultant of the test specimen in the transverse-A orientation was calculated.

For measuring the magnetic field strength, each of the test specimens including the rectangular CM test specimens, POF magnetic PE pipe, or POF longitudinal sectors was always placed at a distance of 30 inches from the magnetometer probe on the same wood board surface, as shown in Figures 16 to 18. Also, it should be noted that the magnetic field measurements reported below are IN-PLANE measurements.

It should be noted that near-field and far-field magnetic effects are associated with the test specimen position and orientation relative to the magnetometer probe; these effects contribute to the magnetic field measurements. In the axial, transverse-A, and 45-degree positions the near-and far-field magnetic effects are similar because all measurements are made with the specimen end-face in-line with the probe; hence, an analysis comparing the magnetic field along the axial, 45-degree, and transverse-A positions would be justifiable and meaningful since all the specimen's measurements are made relative to the same reference- the specimen's end-face. However, in the transverse-B position, as shown in Figure 18 (a) and (b), the field strength measurement in the transverse orientation is a "near-field" measurement because the specimen's centerline is in-line with the probe; hence, in the transverse-B position the near-field effects are more dominant. In the axial orientation, as shown in Figure 16, the specimen's longitudinal length is pointing away from the probe; hence, the field strength measurement along the axial orientation is a far-field measurement compared to the transverse-B orientation. Therefore, comparing the axial, or the 45-degree with the transverse-B measurements is not appropriate and would lead to erroneous conclusions.

In many experiments, the magnetic field was measured for several replicate test samples of the same size and having the same content of magnetic powder and percent weight amount. In cases involving measurements of several replicate samples, the average or mean resultant value of all the samples in a set was calculated and reported.

All of the reported magnetic field measurements are presented in units of Nano-Tesla (nT); 1 Tesla (T) = 10^4 Gauss (G).

MAGNETIC FIELD STRENGTH MEASUREMENTS OF NEWLY MADE COMPRESSION MOLDED PE PLAQUE MATERIALS AXIALLY MAGNETIZED USING PULSE AXIAL MAGNETIZERS

During the current Fourth Milestone phase, numerous magnetization experiments were performed to compare and determine the advantages and limitations of transverse spiral magnetization (TSM) obtained with a rotating magnetizer as utilized with the POF pipe, transverse magnetization (TM) obtained using a stationary magnetizer, and axial magnetization using the Pulse Axial Magnetization (PAM) equipment. These experiments were conducted on several test specimens, including the newly made CM PE plaque materials and longitudinal sectors cut from the POF pipe. These experiments were also performed to determine the effects on the magnetic field of several variables including different types and amounts of magnetic powder material, the number and spacing of the induced dipoles, number of pulses conducted to create a dipole, and the alignment of dipoles.

The laboratory test results showed that TM induces dipoles across the pipe diameter with a resultant field equal to that induced with spiral TSM. Also, the test results showed that PAM has the advantage of inducing dipoles along the axial direction with a period that can be easily altered and used to identify the type of field application. The laboratory tests showed that PAM has also the advantage of inducing a field with a resultant strength that can be easily increased or decreased. Most importantly, the test results demonstrated that for test specimens with the same type and percent weight of magnetic powder, PAM induces a field greater than that induced with either TM or TSM.

To verify the reproducibility of GTI approach and test results, GTI made several new magnetic CM plaque test materials using several different types and concentrations of magnetic materials including the two recently identified MQP 16-7 and HM 185. GTI provided these magnetic CM PE plaque materials and pipe specimens to another organization- -DEXTER MAGNETICS, INC. - - for axial magnetization. DEXTER magnetized these CM PE plaque specimens and pipe specimens independently of GTI using their own magnetization equipment, induction coils, and techniques and procedures. Following receipt of the specimens magnetized by DEXTER, GTI measured their magnetic field strength. Then, GTI axially re-magnetized the same CM specimens using GTI PAM equipment and the 11-inch long induction coil shown in Figures 13 and 14. GTI measured the field strength of the GTI-magnetized samples. The test data obtained on the Dexter-magnetized samples were correlated with those obtained on the GTI-magnetized samples to evaluate the reproducibility and accuracy of the data. The correlations showed excellent correlations and reproducibility. The following sections present the laboratory test data and describe the results in more detail.

FIELD STRENGTH MEASUREMENTS OF NEWLY MADE MAGNETIC CM PLAQUE MATERIALS AXIALLY MAGNETIZED BY GTI USING THE PULSE AXIAL MAGNETIZER

During the current Fourth Milestone phase, many laboratory experiments were performed to axially magnetize the newly made magnetic CM PE plaque materials using GTI PAM equipment involving the 11-inch long induction coil. In these experiments, the

magnetic field was induced axially by placing the CM plaque within the 11-inch long coil and pulsing it with the PAM. Following axial magnetization, GTI performed numerous tests to measure the magnetic field of the CM plaques axially-magnetized by GTI using the same magnetometer instrument, probe and techniques as those described above. As reported above, the results indicated that with PAM, an optimum magnetic field is obtained with one pulse and aligned dipoles, i.e. N-S-N-S-N-. For each of these axially magnetized newly made CM plaque materials, the field was measured along the axial-, 45-degree, and transverse-A directions, respectively.

The field strength was experimentally determined for the newly made magnetic CM PE plaque materials consisting of single layers and multiple layers. To obtain these field strength measurements, each test specimen was placed along the axial orientation, 45-degree orientation, and transverse-A orientation, respectively. Then, field measurements were made in accordance with the procedures described above. Also, for comparative evaluations, several tests, were conducted to determine the magnetic field along the transverse-B direction. For these new CM plaque materials, Table 1 lists the x-, y-, and z-components and the resultant of the magnetic field, denoted as R, of test specimens oriented along the axial direction, 45-degree, transverse-A and transverse-B directions, respectively, as depicted in Figures 16 to 19.

Table 1 lists the axial, 45-degree and transverse-A field strength measurements for several single- layer CM plaques made using either the Nb-base MQP 16-7 magnetic powder or the Ba-base HM 185 magnetic powder in different concentrations that included 24%w, 18%w, and 12%w, respectively. Also, for reference, the magnetic field measurements along the transverse-B orientation are listed in Table 1.

Table 2 is presented to assist in expeditiously comparing only the resultant magnetic field strength of the CM plaques listed in Tables 1. Table 2 gives the resultant field for plaques made using the same magnetic powder material and concentrations as a function of plaque length. For instance, for plaques made using the MQP 16-7, Table 2 gives the field strength along the axial, 45-degree, and transverse-A orientations, respectively, for each of the three concentrations of magnetic powder: 24%w, 18%w, and 12%w as a function of plaque lengths (8.75-, 17.5-, 26.25-, and 35-inch). Similarly, for plaques containing the HM 185 magnetic powder, Table 2 lists the resultant field along the axial, 45-degree, and transverse-A directions as a function of plaque length for 24%w, 18%w, and 12%w concentrations.

Table 2 shows that plaque materials containing the MQP 16-7 magnetic powder have a resultant field, along the axial, 45-degree, or transverse-A orientation, that is three to four times greater than those measured for plaques containing HM 185 powder. Also, Table 2 shows that the resultant magnetic field of CM plaques decreases with decreasing amounts of magnetic powder and increases with the length of the test specimen.

Table A is prepared to provide a summary of the resultant field strength along the axial, 45-degree, and transverse-A and transverse-B directions as a function of type and amount of magnetic powder material and length of the CM plaque specimen. Table A shows that for the same amount of the magnetic powder and for the same plaque length, CM plaques containing the MQP 16-7 powder have three-to-four times greater field than plaques containing the HM 185 magnetic powder.

TABLE A. SUMMARY OF RESULTANT MAGNETIC FIELD VS TYPE AND CONCENTRATION OF MAGNETIC POWDER

Field Strength of CM Plaques and POF Rectangular Sections versus Type and Concentration of Magnetic Powder and Plaque Length

Length	Resultant along axial direction							Resultant along 45 degree direction						
	24%			18%		12%		24%			18%		12%	
	MQP	HM185	POF**	MQP	HM185	MQP	HM185	MQP	HM185	POF	MQP	HM185	MQP	HM185
8.75	1818	421	85	1562	376	1331	223	1420	364	149	1297	300	950	177
17.5	2384	632	135	2166	544	1610	307	2069	583	232	2013	468	1277	250
35	3090	887	181	2802	722	2621	416	2661	780	327	2411	628	1415	356

Length	Resultant along transverse A direction							Resultant along transverse B direction						
	24%			18%		12%		24%			18%		12%	
	MQP	HM185	POF	MQP	HM185	MQP	HM185	MQP	HM185	POF	MQP	HM185	MQP	HM185
8.75	1172	279	101	1013	244	833	135	988	318	192	932	256	788	153
17.5	1879	519	194	1761	421	1197	208	2065	554	376	1800	462	1067	309
35	2767	777	306	2262	642	1309	366	2899	795	620	2668	640	2436	421

****POF:** for comparative evaluations of the field strength of the POF pipe with 24%w HM 130 powder, 2.25-inch wide rectangular sectors were cut from the as-received POF transversely magnetized pipe; . Resultant magnetic field for these POF sectors was measured and compared with that of the CM plaques.

For reference purposes, Tables 1, 2, and A also list the resultant field along the transverse-B orientation. However, it should be emphasized that the near-field effects are more dominant along the transverse-B orientation and hence should not be compared to those measured along the axial, 45-degree, or transverse-A directions which are measured relative to another reference location that is less affected by the near-field.

To illustrate graphically the effects on the magnetic field of the type and amount of magnetic powder used in making the PE plaque materials, the test data in Table A are presented graphically in Figures 20 to 22.

Figure 20 is a linear plot of the resultant field as a function of length of CM plaque test specimens made with 24%w of magnetic powder materials: MQP 16-7, and HM 185, respectively. Figure 20 shows plots of the axial, 45-degree, and transverse-A field strengths for the newly made CM plaque materials. Similarly, for CM plaque materials containing 18%w and 12%w, respectively, of magnetic powder materials MQP and HM 185, Figures 21 and 22 present linear plots of the field strengths along the axial, 45-degree, and transverse-A directions as a function of specimen length. Figures 19 to 21 show the best-fit linear regression lines for the plotted data.

To compare the field strength of the newly made magnetic plaque materials with that induced in the POF pipe manufactured with 24%w HM 130 magnetic powder, longitudinal

sectors were cut from this reference POF pipe. Each POF-sector specimen was cut into a size that contained a weight percent of magnetic powder approximately equal to that used in a comparable CM plaque specimen. Figure 20 shows the resultant field for specimens made using 24%w of magnetic powder. To compare the field strengths using Figure 20, plots are also presented of the field along the axial, 45-degree, and transverse-A directions for the longitudinal POF-pipe-sectors.

It is to be noted that the resultant field measured along the axial direction of a CM plaque is greater than that measured along the 45-degree or the transverse-A direction. The field strength is maximum along the axial direction and decreases with the orientation of the plaque test specimen, relative to the probe, and attains a minimum value along the transverse-A orientation. This decrease in field strength with orientation is due to the fact that the CM plaques were axially magnetized using pulse axial magnetization (PAM) techniques and hence they have the greatest resultant field when measured in the axial direction. However, for the transverse (spirally) magnetized POF pipe, the field strength attains a maximum value along the 45-degree orientation..

Figures 19 to 21 show that the field strength along the axial, 45-degree, and transverse-A obtained using the MQP magnetic powder is more than four times greater than that induced with the HM 185 powder. The data presented in these graphical plots indicate that the field increases with increasing specimen length. Furthermore, these Figures show that the field along the axial direction is several times greater than the field along the transverse-A direction for plaque materials containing MQP and HM 185 powder materials.

Most importantly, Figure 20 shows that the field strengths along the axial, 45-degree, and the transverse-A orientation of plaques made with as little as 12%w of the HM 185 powder are greater than those measured for equivalent sections of the POF pipe containing as much as 24%w of the HM130 magnetic powder.

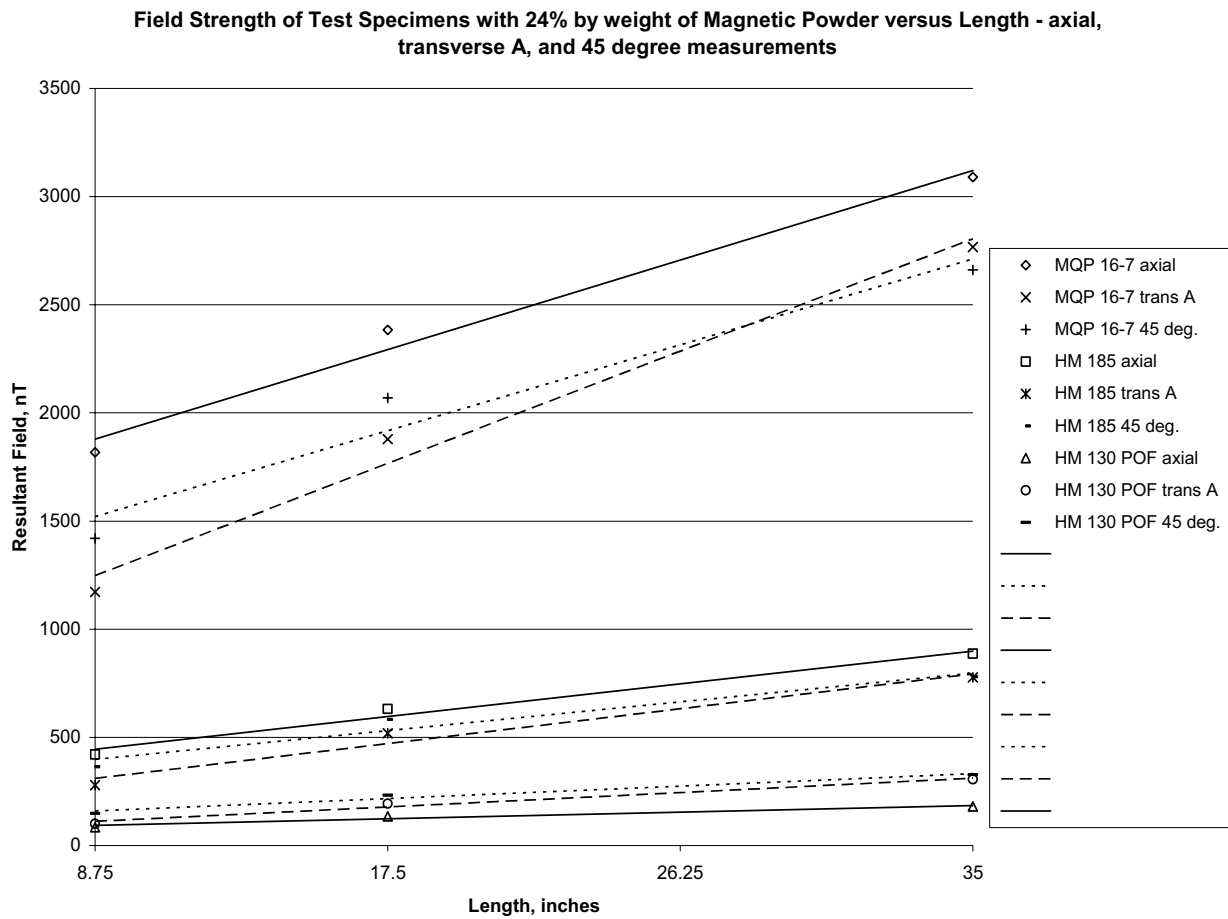


Figure 20. Field strength of CM plaque materials containing 24%w of magnetic powder materials MQP, HM 185, and POF HM 130, respectively versus length

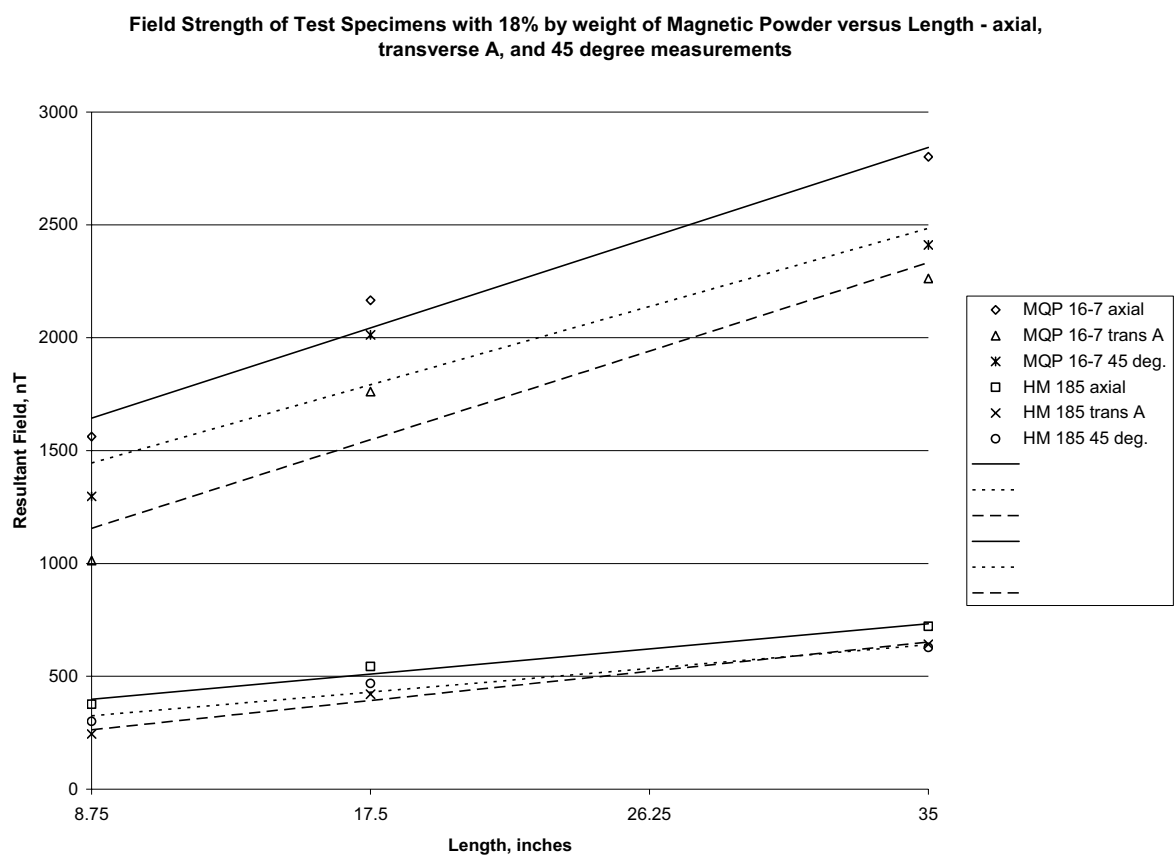


Figure 21. Field strength of CM plaque materials containing 18%w of magnetic powder materials MQP and HM 185 versus length

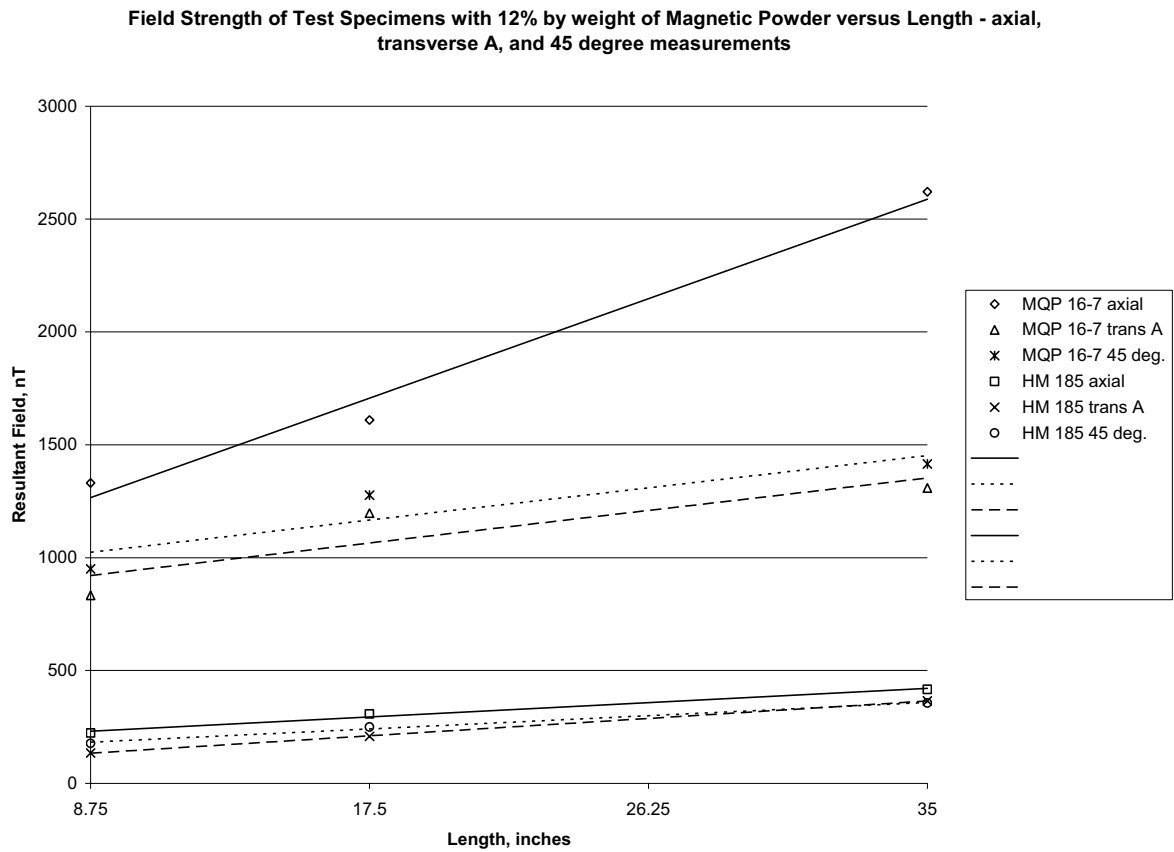


Figure 22. Field strength of CM plaque materials containing 12%w of magnetic powder materials MQP and HM 185 versus length

FIELD STRENGTH MEASUREMENTS OF CM PLAQUES AXIALLY MAGNETIZED BY DEXTER MAGNETICS, INC USING PULSE AXIAL MAGNETIZATION EQUIPMENT

To verify the magnetization methods and test results, several of the magnetic CM PE plaque specimens were magnetized by both DEXTER MAGNETICS, INC and GTI, respectively. The magnetic CM PE plaques were first provided to DEXTER. Dexter completed the axial magnetization of the subject PE CM plaque materials using their own PAM equipment and induction coils and techniques. In addition to the above described CM plaques, GTI also made under laboratory conditions several additional 1-, 2- and 3-layer CM plaques containing different amounts of magnetic material; these additional plaques were also provided to Dexter for axial magnetization. Following receipt of the DEXTER-magnetized CM plaques, GTI measured the magnetic field strength of these plaques. Then, GTI re-magnetized axially the same CM plaques using GTI PAM equipment and the 11-inch long induction coil shown in Figures 10 to 13. GTI measured the magnetic field of GTI-magnetized CM plaques and the DEXTER-magnetized plaques using the same magnetometer instrument, probe and techniques as described above. The magnetic field strength measurements obtained on the DEXTER-magnetized samples were then compared with those obtained on GTI-magnetized samples. The good correlation of test data obtained using Dexter-magnetized samples and GTI-magnetized samples, verified the accuracy and applicability of GTI laboratory magnetization work including test equipment, approach, magnetization techniques. The good agreement of the test data obtained for the Dexter-magnetized and GTI-magnetized samples showed excellent reproducibility and laboratory-to-laboratory repeatability.

The field strengths of the Dexter-magnetized CM plaques were measured and compared with those measured for the same plaque samples but magnetized by GTI. The x-, y-, and z- components and the resultant of the magnetic field were measured for the Dexter-magnetized CM plaques using the same magnetometer and methods as those described above. In one set of measurements, each of the Dexter-magnetized plaque was placed axially to and at a distance of 30 inches from the probe. In another set of measurements, each plaque was placed in a transverse-B position and at a distance of 30 inches from the probe.

Table 3 gives for the CM plaques magnetized by Dexter, the measured field components and resultants along the axial and transverse-B directions.

To assist in quickly comparing the test data obtained on the Dexter-magnetized samples with those obtained on the GTI-samples, Table 4 is prepared.

Table 4 presents in a summary form the data on the resultant field strength, measured along both the axial and transverse-B orientations, for a few of the plaques magnetized by Dexter. To compare the resultant field strength data obtained on the Dexter-magnetized CM samples with those obtained on the same CM samples but as magnetized by GTI, Table 4 also presents the field strength data generated on the same plaques as magnetized by GTI. The comparative test data presented in Table 4 show that the resultant field induced by Dexter along the axial or transverse-B orientation of the plaque materials is approximately within about 10% of the resultant field induced by GTI in the same plaque materials along those orientations.

The good correlation of the resultant field strength data between the Dexter-magnetized samples and GTI-magnetized samples is remarkable especially in view of the fact that Dexter and GTI used totally different axial magnetizers, equipment, approaches and techniques. The excellent correlation between the GTI and Dexter results verify not only the test results and their reproducibility but also demonstrate the accuracy of the approach and techniques used by GTI and indicate that full magnetic saturation was induced in the CM plaque test specimens.

FIELD STRENGTH MEASUREMENTS OF THE REFERENCE POF PIPE CONTAINING 24%w of HM 130 MAGNETIC POWDER

The POF magnetic HDPE pipes containing 24% w strontium-barium-ferrite (Sr/Ba) HM 130 magnetic powder is used as a benchmark reference (control). The POF pipe is used as a reference because- based on field tests- they have an acceptable magnetic field strength that can be located from about 3-feet above ground. It should be emphasized that in the POF pipes, the magnetic spiral field was induced transversely using the rotating PM magnetizer.

Several analytical evaluations were undertaken to compare the magnetic field strength induced in the CM PE plaque materials made by GTI using the new magnetic powder materials MQP and HM 185 with the magnetic field induced in the POF pipe. To perform these comparative evaluations, several longitudinal sectors were cut from the POF pipes. To prepare the POF pipe sectors, the POF pipe was first cut into several rings of different longitudinal lengths including: 8.75-, 17.5-, and 35-inch. Each ring was then cut into several sectors with a width of about 2.125-inch. Each sector was of approximately equal weight as a CM plaque of the same length.

For the POF pipe samples and longitudinal sector specimens cut-out from the POF pipe, the same test procedures as those described above were implemented for measuring the magnetic field along the axial, 45-degree, and transverse orientations, respectively.

The resultant field strengths of the POF pipe samples and the POF rectangular sectors were then measured using the same fluxgate magnetometer probe and the same procedures and techniques as those used with the magnetic CM PE plaques. The field strength of each POF pipe sample and POF sector was measured along the axial, 45-degree and the transverse-A and transverse-B orientations, respectively. The field strengths of the POF pipe sectors were then compared with those of the CM plaques made with the MQP 16-7 and the HM185 magnetic powders having different concentrations.

Table 5 gives the x-, y-, and z-components and the resultant field for the POF pipe samples and the POF rectangular sectors, cut from the POF pipe, measured along the axial, and 45-degree direction. For reference, Table 5 also lists the field along the transverse-B orientation for the POF test samples. Tables 1 and 2 also list the field strength resultants measured along the transverse-A direction for the POF sectors. Again, it should be noted that for the POF pie sectors, the field strength along the axial, 45-degree, and the transverse-A directions were determined relative to the same reference- - specimen end-face; however, the transverse-B measurement was performed relative to the mid-section of the specimen.

Table 1,2, and 5 show that the field strength of the POF sector has a maximum value along the 45-degree direction. This is due to the fact that the as-received POF pipe, from which the sectors were cut, was magnetized transversely. Also Table 5 shows that the field

strength in either the axial or transverse orientation increases with increasing sector longitudinal length.

Table 5 indicates that the field strength of the full POF pipe specimen is about two to three times greater than that measured for the POF sector. For instance, for an 8-inch length the sector has field resultants of about 85nT and 192 nT along the axial and transverse directions, respectively. Whereas for the full-scale 8.75-inch pipe specimen, the axial and transverse resultants are about 226 nT and 574 nT, respectively. As reported previously, Tables 5 also show that the field strengths of the POF sectors or pipe specimens increase with increasing specimen length.

COMPARATIVE EVALUATIONS OF FIELD STRENGTH INDUCED IN NEWLY MADE MAGNETIC PLAQUE MATERIALS WITH FIELD STRENGTH OF REFERENCE POF PIPE

To compare and correlate the field strength test data obtained with newly-made CM plaque materials with that for the reference manufactured POF pipe, the approach involving the use of POF pipe sectors was determined to be the most accurate because it involved the comparative evaluations of materials having an equivalent weight. That is, the POF pipe sectors have approximately an equivalent average weight % of magnetic powder to PE as the CM plaques. This comparative approach led to reasonably accurate and expedient comparisons of the field strength of various CM plaque materials with that of the POF pipe.

Table A gives a summary of the test data comparing the resultant field strength for the CM plaque materials containing the new magnetic powder materials MQP and HM 185 with the resultant field strength obtained for the reference POF pipe sectors manufactured with HM 130 magnetic powder.

Table A shows that the field strengths in the axial, 45-degree, and transverse-A directions of the CM plaque materials made with 24%w, 18%w, or 12%w of the MQP powder are more than four times greater than the corresponding field strength of the POF rectangular sectors. Hence, this indicates that even as little as 4%w of the MQP powder would result in an induced field greater than the reference POF with 24%w of HM 130.

Table A shows that the field strengths along the axial, 45-degree, and transverse-A directions of the CM plaque materials made with 24%w or 18%w of the HM 185 magnetic powder are significantly greater than the corresponding field strengths of the POF sectors material. Most importantly, Table A shows that for plaque specimens made with as little as 12%w of HM 185 powder, the field strengths along the axial, 45-degree, and transverse-A directions are greater than the corresponding field strengths measured for the POF sectors.

To assist in visually comparing the field strengths of the newly made magnetic materials with the reference POF sector materials containing 24%w of HM 130, the test data in Table A are plotted graphically in Figures 23 to 25. Figures 23 to 25 are graphical plots depicting the field strengths, along different directions, for 8.75-, 17.5-, and 35-inch long, respectively, of test specimens made of the new magnetic materials and POF pipe sector specimens.

Figure 23 is a linear plot of the resultant field strengths of the 8.75-inch long PE CM plaque material as a function of the type and amount (weight percent) of magnetic powder. For a 8.75-inch long plaque, Figure 23 presents plots of the field strength data, along the

axial, 45-degree, and transverse-A directions, respectively, for materials made with Nb-base MQP 16-7 magnetic powder and Ba-base HM 185, and POF HM 130 magnetic powder.

Figures 24 and 25 present similar plots of the axial, 45-degree, and transverse-A field strengths for the 17.5-inch and 35-inch long plaques, respectively, as a function of the type and amount of magnetic powders MQP and HM185. Figures 23 to 25 also show the axial, 45-degree and transverse-A field strengths for longitudinal sectors of the reference POF pipe manufactured using 24%w HM 130 magnetic powder. These Figures present the best-fit linear regression lines for the test data.

The data presented in these graphical plots indicate that the field increases with increasing specimen length. Furthermore, these Figures show that the field along the axial direction is about twice the field along the transverse-A direction for plaque materials containing MQP and HM 185 powder materials. Figures 23 to 25 show that the axial, 45-degree, and transverse-A field strengths obtained using the MQP magnetic powder is more than four times greater than that induced with the HM 185 powder.

Most importantly, Figures 23 to 25 show that the axial, 45-degree or transverse-A field strength for plaques containing only 12%w of the MQP magnetic powder is several times greater than those measured for the POF sector containing as much as 24%w HM 130 powder.

Also, Figures 23 to 25 show that the field strength along any orientation for plaques containing only 12%w of the HM185 magnetic powder is greater than that measured for the POF sectors containing as much as 24%w HM 130 powder.

Graphically, Figures 23 to 25 indicate that the axial, 45-degree, or the transverse-A field strength obtained using as little as 6%w of the MQP magnetic powder would be greater than that of the POF sectors made with 24%w HM 130 powder.

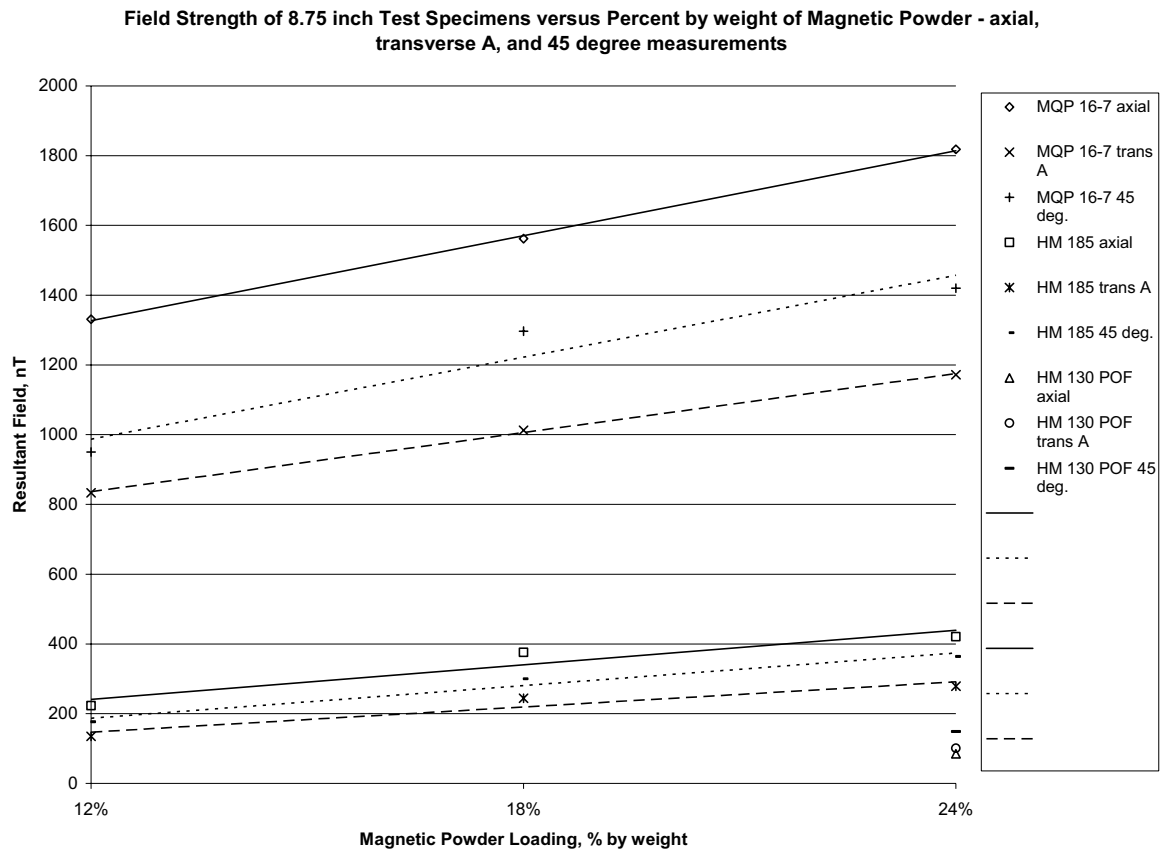


Figure 23. Field strength of 8.75-inch long plaque materials containing different types and amounts of magnetic powder and POF sectors cut from POF pipe

Field Strength of 17.5" Test Specimens versus Percent by weight of Magnetic Powder - axial, transverse A, and 45 degree measurements

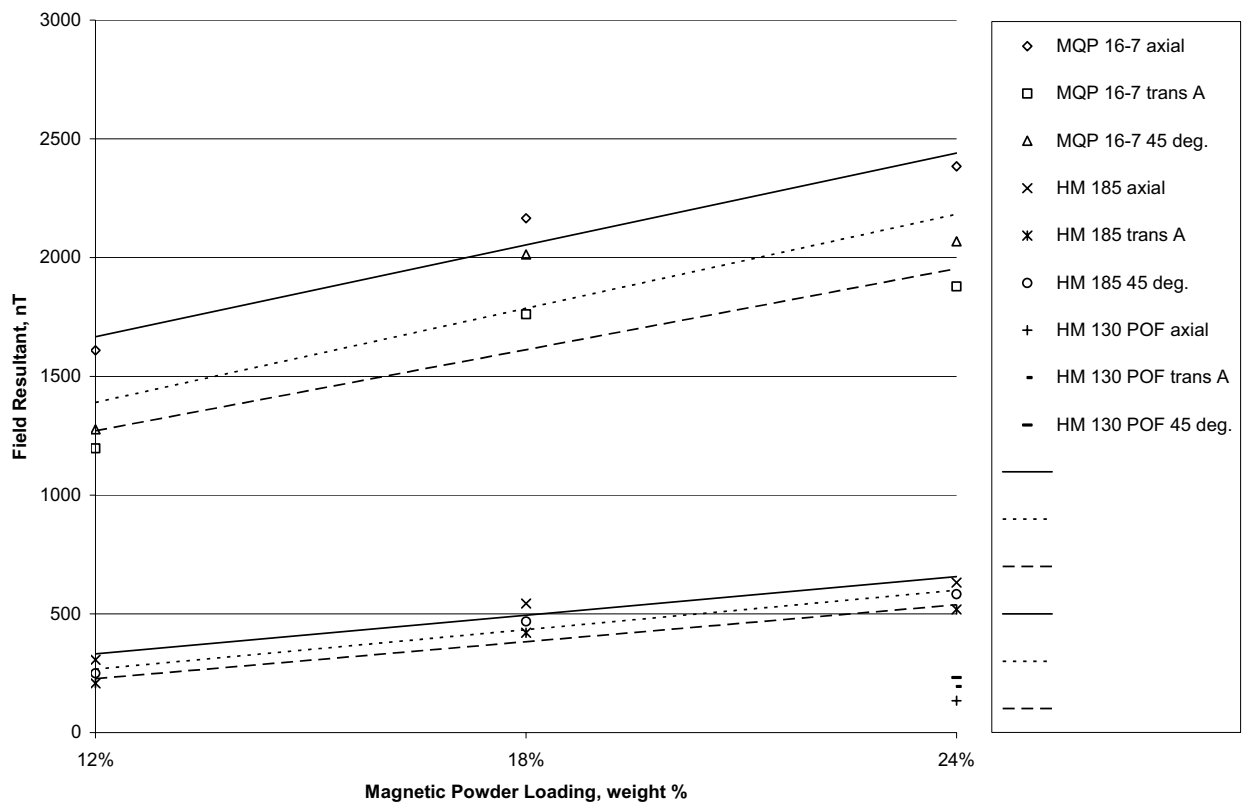


Figure 24. Field strength of 17.5-inch long plaque materials containing different types and amounts of magnetic powder and POF sectors cut from POF pipe

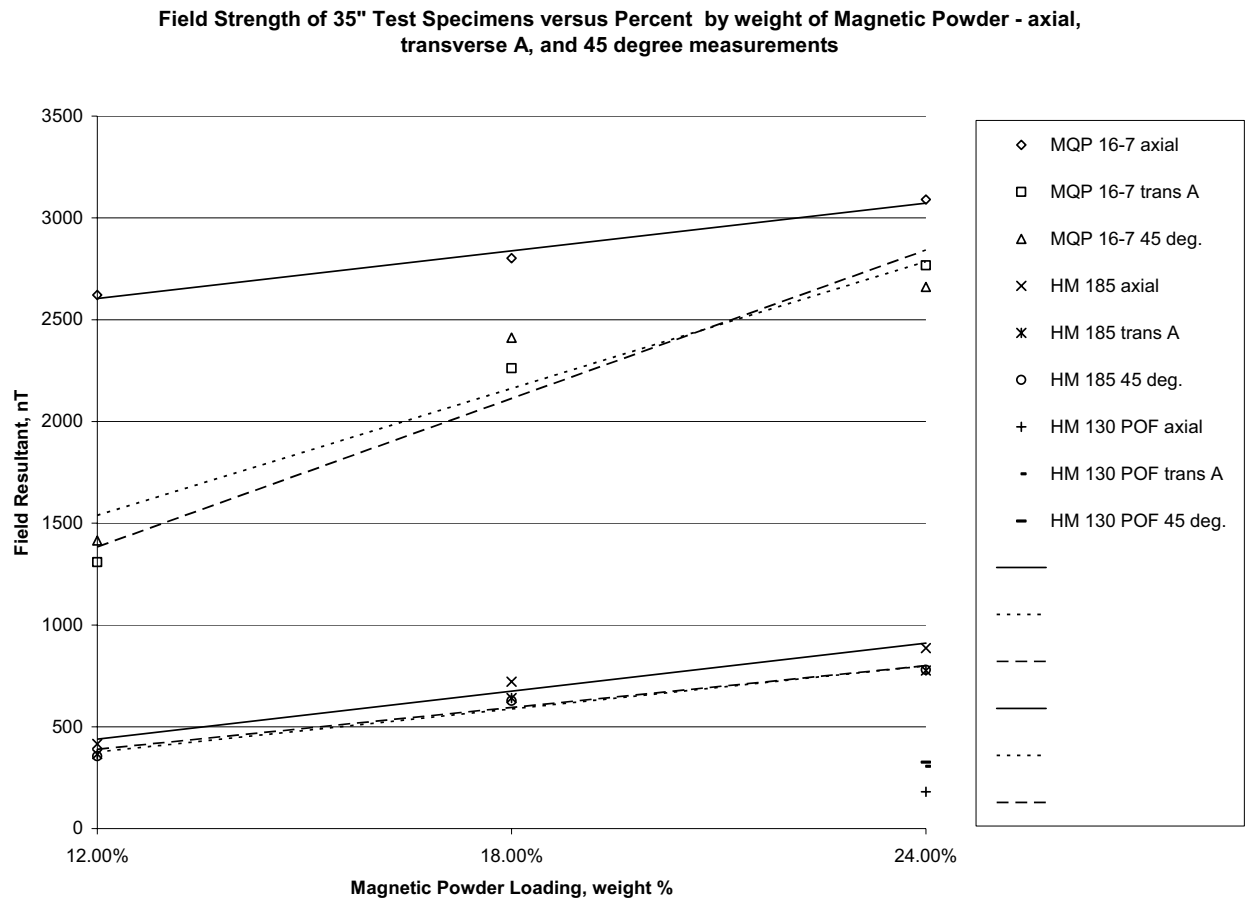


Figure 25. Field strength of 35-inch long plaque materials containing different types and amounts of magnetic powder and POF sectors cut from POF pipe

RESULTS AND CONCLUSIONS

Many important results, findings and conclusions were established and validated in the subject DOT project. The most important conclusion is that new plastic PE pipe materials containing less than about 6%w of the newly identified magnetic powder MQP have a sufficiently high magnetic field that would allow them to be readily located from a distance of three-to-five feet from above ground.

Several additional important results and findings are summarized as follows:

- The laboratory tests showed that plaques made with about 6%w of the Nb-base MQP 16-7 magnetic powder have substantially greater field strength than that measured for the POF pipes made with 24%w of HM 130 magnetic powder.
- Numerous laboratory tests showed that for the same weight percent or amount of magnetic powder, the field strength of new plaque materials made with the Nb-base MQP 16-7 magnetic powder is greater than that of the CM plaques made with HM 185 magnetic powder.
- The laboratory test data showed that the magnetic field of the new plaque materials made with 12%w of the Ba-base HM 185 powder is greater than the field measured for the previous POF pipe materials containing as much as 24%w of the HM 130 powder.
- The amount of magnetic powder can be reduced to less than about 6% by weight (%w) using Nb-base MQP 16-7 magnetic powder. With 12%w of the MQP 16-7 powder, the field strength is several times greater than the POF magnetic PE pipes containing 24%w of HM 130 magnetic powder.
- Many laboratory tests performed on the new magnetic PE plaque materials showed that axial magnetization can induce a greater magnetic field and can provide many additional advantages compared to transverse magnetization or spiral magnetization.
- Axial magnetization is superior to transverse or spiral magnetization for optimizing the magnetic field strength and the consequent detection of the underground magnetized plastic pipe.
- The laboratory tests showed that pulse axial magnetization (PAM) has the advantage of inducing a magnetic field with a resultant strength that can be easily increased or decreased during pipe manufacturing.
- Also, the test results showed that PAM has the advantage of inducing dipoles along the axial direction with a period that can be easily altered and used to identify the type of pipe field application.
- Several laboratory tests showed that with axial magnetization, the field strength in the pipe specimen or the CM plaque is optimum with induced aligned dipoles, i.e. N-S-N-S-N-S ...compared to that induced with opposite dipoles, i.e. N-S-S-N-N-S-S-N-....
- Most importantly, the test results demonstrated that for test specimens with the same type and percent weight of magnetic powder, PAM induces a field greater than that induced with either transverse magnetization (TM) or spiral magnetization (SM).

- The magnetic field strength is the same for the same concentration of the magnetic powder per unit volume of pipe/plaque material. The greater the magnetic powder concentration per unit volume of the total material the greater is the field. Hence, concentrating the magnetic powder in a surface strip or in a co-extruded layer would provide a stronger localized magnetic field than uniformly distributing the magnetic powder over the entire pipe volume.
- The laboratory tests showed that the magnetic field strength increases with increasing length of plaque or pipe test specimen and attains a maximum asymptotic constant value for a specimen length of about 30 to 48 inches.
- Also, many experiments showed that for pipes magnetized axially, the greatest detectable field is obtained by traversing the pipe axially; the detectable field decreases with the orientation of the pipe locator relative to the pipe. That is, for pipes magnetized axially using the axial pulse magnetizer, the greatest magnetic detectable field is obtained by orienting the pipe collinearly with or by traversing the pipe axially relative to the locating magnetometer instrument.
- The laboratory test results showed that TM induces dipoles across the pipe diameter with a resultant field equal to that induced with spiral TSM.

TABLE 1

Field Strength Along Axial, 45-degree and Transverse Directions of CM Plaques Magnetized by GTI Using New 11-inch Coil and Pulse Axial Magnetizer (PAM) at 600 volts DC, nanoTesla (nT)*

24% Nb MQP 16-7, 205g/650g PE, CM plaque, PAM magnetized

Axial orientation

Length*	X	Y	Z	R
8.75	1817	61	10	1818.05
17.5	2383	66	4	2383.92
26.25	2896	63	11	2896.71
35	3089	57	14	3089.56

Transverse A orientation

Length	X	Y	Z	R
8.75	448	1083	31	1172.41
17.5	1162	1476	33	1878.81
26.25	~	~	~	~
35	2393	1389	28	2767.05

Transverse B orientation

Length	X	Y	Z	R
8.75	81	984	27	987.697
17.5	232	2051	71	2065.3
26.25	381	2827	90	2853.98
35	250	2885	106	2897.75

45 degree orientation

Length	X	Y	Z	R
8.75	1321	522	10	1420.43
17.5	1980	600	12	2068.95
26.25	~	~	~	~
35	2611	511	8	2660.55

18% Nb MQP 16-7 143g/650g PE, CM plaque, PAM magnetized

Axial orientation

Length	X	Y	Z	R
8.75	1560	76	8	1561.87
17.5	2166	41	12	2166.42
26.25	2546	81	6	2547.3
35	2801	76	8	2802.04

Transverse A orientation

Length	X	Y	Z	R
8.75	368	943	27	1012.62
17.5	1079	1392	23	1761.37
26.25	~	~	~	~
35	1844	1310	19	2262.03

Transverse B orientation

Length	X	Y	Z	R
8.75	49	931	3	932.293
17.5	161	1792	44	1799.76
26.25	89	2055	85	2058.68
35	67	2666	82	2668.1

45 degree orientation

Length	X	Y	Z	R
8.75	1208	471	7	1296.59
17.5	1933	562	8	2013.06
26.25	~	~	~	~
35	2359	499	2	2411.2

12% Nb MQP 16-7 89g/650g PE, CM plaque, PAM magnetized

Axial orientation

Length	X	Y	Z	R
8.75	1331	21	14	1331.24
17.5	1610	26	16	1610.29
26.25	1696	24	9	1696.19
35	2615	171	15	2620.63

Transverse A orientation

Length	X	Y	Z	R
8.75	344	759	14	833.434
17.5	802	889	8	1197.33
26.25	~	~	~	~
35	994	851	3	1308.53

Transverse B orientation

Length	X	Y	Z	R
8.75	5	787	41	788.083
17.5	244	1038	37	1066.93
26.25	363	1186	35	1240.8
35	246	2423	39	2435.77

45 degree orientation

Length	X	Y	Z	R
8.75	907	281	1	949.532
17.5	1242	299	3	1277.49
26.25	~	~	~	~
35	1389	272	2	1415.38

TABLE 1 (cont'd)

24% HM 185, 173g/547g PE, CM plaque, PAM magnetized

Axial orientation

Length	X	Y	Z	R
8.75	421	1	7	421.059
17.5	632	2	8	632.054
26.25	762	6	5	762.04
35	~	~	~	~

Transverse A orientation

Length	X	Y	Z	R
8.75	112	256	3	279.444
17.5	352	381	3	518.723
26.25	~	~	~	~
35	702	332	9	776.601

Transverse B orientation

Length	X	Y	Z	R
8.75	59	312	6	317.586
17.5	80	548	2	553.812
26.25	106	733	8	740.668
35	~	~	~	~

45 degree orientation

Length	X	Y	Z	R
8.75	341	126	1	363.535
17.5	565	144	2	583.065
26.25	~	~	~	~
35	772	114	1	780.372

18% HM 185, 130g/590g PE CM plaque, PAM magnetized

Axial orientation

Length	X	Y	Z	R
8.75	376	10	14	376.393
17.5	544	9	12	544.207
26.25	664	9	12	664.169
35	722	5	16	722.195

Transverse A orientation

Length	X	Y	Z	R
8.75	104	221	4	244.281
17.5	280	315	5	421.485
26.25	~	~	~	~
35	578	279	12	641.926

Transverse B orientation

Length	X	Y	Z	R
8.75	16	255	16	256.002
17.5	21	461	14	461.69
26.25	20	582	18	582.622
35	23	639	20	639.727

45 degree orientation

Length	X	Y	Z	R
8.75	288	84	4	300.027
17.5	457	101	1	468.029
26.25	~	~	~	~
35	621	93	2	627.928

12% HM 185, 89g/650g PE, CM plaque, PAM magnetized

Axial orientation

Length	X	Y	Z	R
8.75	223	4	2	223.045
17.5	307	9	4	307.158
26.25	380	3	7	380.076
35	416	4	2	416.024

Transverse A orientation

Length	X	Y	Z	R
8.75	61	120	1	134.618
17.5	135	158	3	207.841
26.25	~	~	~	~
35	341	133	8	366.107

Transverse B orientation

Length	X	Y	Z	R
8.75	26	151	8	153.431
17.5	26	308	6	309.154
26.25	71	367	9	373.913
35	40	419	7	420.963

45 degree orientation

Length	X	Y	Z	R
8.75	173	38	3	177.15
17.5	246	45	2	250.09
26.25	~	~	~	~
35	355	32	4	356.462

TABLE 1 (cont'd)

24% HM 130 POF Rectangular Sections, Transversely Magnetized Using PM**

Axial orientation

Length	X	Y	Z	R
8.75	11	81	29	86.735
17.5	27	127	31	133.488
26.25	~	~	~	~
35	7	176	28	178.351

Transverse A orientation

Length	X	Y	Z	R
8.75	49	88	1	100.727
17.5	145	129	2	194.088
26.25	~	~	~	~
35	286	109	6	306.126

Transverse B orientation

Length	X	Y	Z	R
8.75	187	40	12	191.606
17.5	361	57	54	369.440
26.25	~	~	~	~
35	617	45	33	619.518

45 degree orientation

Length	X	Y	Z	R
8.75	146	27	4	148.529
17.5	230	31	3	232.099
26.25	~	~	~	~
35	326	25	4	326.982

*Typical plaque width is 2.1 - 2.2 inches

****POF:** for comparative evaluations of the field strength of the POF pipe with 24%w HM 130 powder, 2.25-inch wide rectangular sectors were cut from the as-received POF transversely magnetized pipe; . Resultant magnetic field for these POF sectors was measured and compared with that of the CM plaques.

TABLE 2

**Resultant Magnetic Field Along axial and Transverse Directions of
CM Plaques Magnetized Axially by GTI Using PAM, as a Function of
Type and Concentration of Magnetic Powder and Plaque Length, nT**

		Resultant			
	Length	Axial	45 deg.	Trans A	Trans B
24% MQP 16-7 1 Layer Plaque	8.75"	1818	1420	1172	988
	17.5"	2384	2069	1879	2065
	26.25"	2897	~	~	2854
	35"	3090	2661	2767	2899
18% MQP 16-7 1 Layer Plaque	8.75"	1562	1297	1013	932
	17.5"	2166	2013	1761	1800
	26.25"	2547	~	~	2059
	35"	2802	2411	2262	2668
12% MQP 16-7 1 Layer Plaque	8.75"	1331	950	833	788
	17.5"	1610	1277	1197	1067
	26.25"	1696	~	~	1241
	35"	2621	1415	1309	2436
24% HM 185 1 Layer	8.75"	421	364	279	318
	17.5"	632	583	519	554
	26.25"	762	~	~	741
	35"	887	780	777	795
18% HM 185 1 Layer Plaque	8.75"	376	300	244	256
	17.5"	544	468	421	462
	26.25"	664	~	~	583
	35"	722	628	642	640
12% HM 185 1 Layer Plaque	8.75"	223	177	135	153
	17.5"	307	250	208	309
	26.25"	380	~	~	374
	35"	416	356	366	421
POF MAG 24 8.75" sections	8.75"	85	149	101	192
	17.5"	135	232	194	376
	26.25"	~	~	~	~
	35"	181	327	306	620

TABLE 3

**Field Strength Measurements along Transverse B and Axial Orientations of CM plaque samples
Axially Magnetized by Dexter Magnetics Using Pulse Axial Magnetizer, nanoTesla (nT)**

24% MQP16-7, 205g/650g PE,CM plaques

transversely B oriented					axially oriented				
Sample #	X	Y	Z	R	Sample #	X	Y	Z	R
8.75"	212	1179	41	1198.61	8.75"	1752	31	16	1752.35
17.5"	285	2090	140	2113.98	17.5"	2599	46	22	2599.5
26.25"	164	2329	102	2336.99	26.25"	2977	63	29	2977.81
35"	506	3089	85	3131.32	35"	3164	83	24	3165.18

26% MQP16-7 210g/600g PE 3 layer CM plaques

transversely B oriented				
Sample #	X	Y	Z	R
8.75"	59	1358	41	1359.9
17.5"	249	1929	73	1946.37
26.25"	711	2297	119	2407.47
35"	553	2796	102	2851.99

18% MQP16-7, 143g/650g PE CM plaques

transversely B oriented					axially oriented				
Sample #	X	Y	Z	R	Sample #	X	Y	Z	R
8.75"	54	885	9	886.692	8.75"	1447	32	11	1447.4
17.5"	95	1562	32	1565.21	17.5"	2303	38	9	2303.33
26.25"	148	1855	45	1861.44	26.25"	2638	44	11	2638.39
35"	285	2083	36	2102.71	35"	2841	46	11	2841.39

12% MQP16-7, 89g/650g PE CM plaques

transversely B oriented					axially oriented				
Sample #	X	Y	Z	R	Sample #	X	Y	Z	R
8.75"	109	490	15	502.201	8.75"	1370	16	10	1370.13
17.5"	177	734	17	755.231	17.5"	1511	19	10	1511.15
26.25"	236	982	25	1010.27	26.25"	1709	21	10	1709.16
35"	387	1076	29	1143.85	35"	1789	30	9	1789.27

24% HM185, 173g/547g PE CM plaques

transversely B oriented					axially oriented				
Sample #	X	Y	Z	R	Sample #	X	Y	Z	R
8.75"	16	304	11	304.619	8.75"	404	7	12	404.239
17.5"	39	521	35	523.629	17.5"	611	5	12	611.138
26.25"	69	697	77	704.627	26.25"	733	5	11	733.1
35"	39	793	76	797.588	35"	812	6	12	812.111

TABLE 3 (Cont'd)

24% HM185, 173g/547g PE, 3 layer CM plaque

transversely B oriented

Sample #	X	Y	Z	R
8.75"	40	285	15	288.184
17.5"	66	540	29	544.791
26.25"	27	648	48	650.336
35"	37	748	59	751.235

18% HM185, 130g/590g PE CM plaque

transversely B oriented

Sample #	X	Y	Z	R
8.75"	30	234	6	235.992
17.5"	54	422	32	426.643
26.25"	56	532	38	536.287
35"	86	620	56	628.436

axially oriented

Sample #	X	Y	Z	R
8.75"	389	2	10	389.134
17.5"	553	17	12	553.391
26.25"	660	12	11	660.201
35"	727	19	12	727.347

15% HM185 116g/650g PE CM plaque

transversely B oriented

Sample #	X	Y	Z	R
8.75"	16	176	10	177.008
17.5"	25	301	13	302.316
26.25"	31	366	23	368.03
35"	22	410	27	411.477

12% HM185 89g/650g PE Cm plaque

transversely B oriented

Sample #	X	Y	Z	R
8.75"	16	177	21	178.958
17.5"	37	315	42	319.934
26.25"	27	379	37	381.758
35"	24	414	41	416.717

14% HM185, 87g/547g PE CM plaque

transversely B oriented

Sample #	X	Y	Z	R
8.75"	7	126	6	126.337
17.5"	14	225	11	225.703
26.25"	8	297	18	297.652
35"	17	332	26	333.45

axially oriented

Sample #	X	Y	Z	R
8.75"	235	21	7	236.04
17.5"	296	24	12	297.214
26.25"	321	24	6	321.952
35"	369	26	5	369.949

TABLE 4

Comparing Resultant Field Strength of CM Plaques Magnetized Axially by GTI and Dexter Magnetics Using PAM nT

	Length	RESULTANT		RESULTANT	
		Magnetized by GTI		Magnetized by Dexter	
		Trans B orientation	Axial orientation	Trans B orientation	Axial orientation
24% MQP 16-7 1 Layer	8.75"	988	1818	1199	1752
	17.5"	2065	2384	2114	2599
	26.25"	2854	2897	2337	2978
	35"	2899	3090	3131	3165
18% MQP 16-7 1 Layer	8.75"	932	1562	887	1447
	17.5"	1800	2166	1565	2303
	26.25"	2059	2547	1861	2638
	35"	2668	2802	2103	2841
12% MQP 16-7 1 Layer	8.75"	788	1331	502	1370
	17.5"	1067	1610	755	1511
	26.25"	1241	1696	1010	1709
	35"	2436	2621	1144	1784
24% HM 185 1 Layer	8.75"	318	421	305	404
	17.5"	554	632	524	611
	26.25"	741	762	705	733
	35"	795	887	798	812
18% HM 185 1 Layer	8.75"	256	376	236	389
	17.5"	462	544	427	553
	26.25"	583	664	536	660
	35"	640	722	628	727
12% HM 185 1 Layer	8.75"	153	223	126	236
	17.5"	309	307	226	297
	26.25"	374	380	298	322
	35"	421	416	333	370

TABLE 5

Field Strength of POF Transversely Magnetized Pipe Versus Length									
POF Pipe Made Using 24%w HM 130 Powder, nanoTesla (nT)									
Field strength along axial direction					Field strength along transverse B direction				
Length	X	Y	Z	R	Length	X	Y	Z	R
8.75"	13.5	223.5	29.3	225.9	8.75"	572.5	27.8	22.3	573.7
17.5"	30.6	328.8	34.8	339.1	17.5"	1116.1	98.5	53.2	1162.6
35"	45.5	472	31	477.3	35"	1860.5	63.5	31	1862.1
Field Strength of Rectangular Sections cut from POF Transversely Magnetized Pipe									
Made Using 24%w HM 130 Powder, nanoTesla (nT)**									
Field Strength along axial direction					Field Strength along transverse B direction				
Length	X	Y	Z	R	Length	X	Y	Z	R
8.75"	10.8	81	22.8	84.9	8.75"	186.5	39.8	21.3	191.9
17.5"	23.6	126.4	26.6	134.7	17.5"	357	52.3	46	375.9
35"	111.5	178	30	180.9	35"	617	45	33	619.5
Field Strength along 45-degree direction									
Length	X	Y	Z	R					
8.75	146	27	4	148.5295					
17.5	230	31	3	232.0991					
35	326	25	4	326.9817					
**POF: for comparative evaluations of the field strength of the POF pipe with 24%w HM 130 powder, 2.25-inch wide rectangular sectors were cut from the as-received POF transversely magnetized pipe; . Resultant magnetic field for these POF sectors was measured and compared with that of the CM plaques.									